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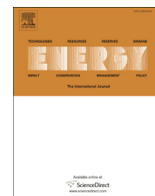
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An energy and carbon life cycle assessment of industrial CHP (combined heat and power) in the context of a low carbon UK



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ABSTRACT

The UK has targets to reduce carbon emissions by 80% by 2050 compared to a 1990 baseline. The Transition Pathways research consortium has generated a set of three low carbon UK electrical futures, together with the corresponding technology mixes. All require a significant amount of technological change, including a significant increase in the contribution of CHP (combined heat and power). This study investigates the appropriateness of industrial CHP as a low carbon electricity generation technology for the UK via an environmental LCA (life cycle assessment) case study of an existing industrial CHP plant in UK. The study shows that harnessing the resource of industrial heat via straight forward CHP conversion can generate electricity with lower associated energy and carbon impacts than the current and the 1990 National Grids. However it is apparent that if the grid successfully reduces in carbon intensity, the technology will come at a comparative carbon cost.

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1. Introduction

In 2010, industrial energy use accounted for approximately 18% of the total UK energy consumption; that is 322 TWh of 1740 TWh [1]. However, the greenhouse gas emissions associated with the industrial sector was reported to be around 33% of the UK total in 2010, that is 191 Mt.CO₂ (equivalent) [2]. This high proportion of emissions is due to the amount of carbon intense technologies and fuels used to generate the process heat energy consumed in the industrial sector [3]. Around 65%, 209 TWh(th), of the energy consumed in the industrial sector in 2010 was used for heat [1]. In 2010, 154 TWh(th) of the heat consumed in the industrial sector was derived from primary fuels, i.e. not from electricity. Natural gas was the predominant fuel, fuelling 50% of the overall industrial heat demand, 105 TWh(th) [1]. Combined heat and power systems, CHP, could be one way that the industrial sector could improve its carbon credentials without changing its fuel or heat demand. CHP technologies use the primary fuel more efficiently by capturing the heat produced in electricity generation, or, to put it conversely, simultaneously generate electricity in the production of useful heat. CHP schemes are most efficient when there is a local and consistent heat

demand so industrial process heating seems an appropriate situation for CHP application. The technology has already been adopted in some industrial systems across the UK to replace heat only systems. The motivation for this technology change for the site itself is often financial [6], but this utilization of industrial heat to generate electricity as a by-product may have the potential to contribute to the UK low carbon electricity future. This study examines the application of industrial CHP as a method for exploiting an existing heat demand in order to generate low carbon electricity in the UK and outlines:

- A carbon and energy life cycle assessment, LCA, case study of an existing industrial CHP plant, including a thorough inventory analysis and results interpretation
- How the energy and carbon savings in operation compare with the energy consumed and carbon emitted in the technology conversion process
- The wider environmental consequences of converting to a CHP scheme, predominately those associated with fossil fuel demand
- The total potential contribution to carbon reduction targets that can be made by industrial CHP in the UK
- The assumptions made and the data generated so that the results of this case study can be of benefit to those wishing to further investigate the role of CHP in alternate future energy scenarios

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Nomenclature

CCS	carbon capture and storage
CED	cumulative energy demand
CHP	combined heat and power
DEFRA	Department of Environment, Food and Rural Affairs
DUKES	Digest of United Kingdom Energy Statics
EGR	energy gain ratio
EPSRC	Engineering and Physical Science Research Council
EU	European Union
GB	Great Britain
GE	general electric
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organisation
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
UK	United Kingdom

2. Background

In 2010, UK CHP schemes generated 26 TWh(e) and 48 TWh(th) of power and heat respectively, contributing 7% of the UK electricity supply capacity [7] plus 6% of the total heat energy consumed in that year [1]. The UK government reported that the electricity generated by UK CHP systems saved 9.28 Mt.CO₂ equivalent 2010 against the total 'UK basket carbon intensity', i.e. against the same amount of power generated by the National Grid full mix of electricity generators, including nuclear and renewable [8]. 89% of the total UK CHP electrical capacity and 92% of the total heat capacity was within the industrial sector in 2010. The reported actual generation from industrial schemes was 24 TWh(e) of power and 44 TWh(th) of heat in 2010 [7]. It is assumed that the heat is consumed within the sector that it is produced.

2.1. UK wide potential for industrial CHP

A number of studies suggest that there is still an opportunity for CHP roll out in the UK [9] and that industrial CHP is a readily available way to contribute low carbon electricity to the grid mix and make an immediate impact on UK emissions. It is a proven technology that does not incur the sort of localized objection associated with wind farms and nuclear power plants as they are installed in existing industrial sites. However, it is thought by some that the industrial sector is already reaching its viable economic limit for CHP application. It is also argued by some that primary fuelled CHP systems will become an anachronism in a highly electric future [10] and conversion is unjustified as a carbon reduction measure in the long term. If the energy sector is successful in reducing the carbon intensity of grid electricity, there is predicted to be a point at which CHP will cease to offer any benefit over the National Grid mix.

The EU Cogeneration Directive sets down the standard that 'Good Quality' CHP must deliver 10% savings on primary fuel used compared to separate conventional generation [11]. In 2004, the UK government set a goal of installing 10 GW(e) of 'Good Quality' CHP capacity by 2010. That goal was not reached. The slow uptake of the technology has since been blamed on the decreasing 'spark spread' which is the price difference between the primary fuel, predominantly gas, and electricity. This price difference is crucial to assessing the economic viability of a new scheme [8].

Following an economic analysis, DEFRA predicted in 2007 [12] that medium to low temperature industrial CHP capacity would be limited to 5.4 GW(e) in 2010. This figure, is very close to the actual reported figure of 5.3 GW(e) for 2010 [8]. DEFRA also predicted that industrial CHP schemes would be limited to a capacity of 6.8 GW(e) in 2015 [12]. Using a simple linear extrapolation from this small set of figures, a maximum feasible power capacity for industrial CHP in 2050 can be set at 15 GW(e). Extrapolating the historic reported figures for generation to 2050, again using a simple linear extrapolation, a value of 65 TWh(e) can be set for industrial CHP. This implies an additional generating potential of 42 TWh(e). There is no strong evidence to suggest that CHP capacity will increase linearly, however if it is assumed that it will increase then it is the simplest and most transparent trajectory to adopt.

The power capacity of industrial CHP will also, obviously, be limited by the available heat load. Of the heat derived from primary fuels in the industrial sector in 2010, it can be assumed that at least 110 TWh(th) was not supplied by a CHP installation. This energy is highly unlikely to be fully available for CHP application as there is no accounting for the likely technical and economic limitations, for instance, some industrial processes require heat at temperatures above that which can be generated by current CHP technology. Also it does not make any consideration for the potential industrial heat demand that could be met via CHP generated electricity. However, this figure can be used as an estimate for the maximum additional industrial heat demand available for CHP application.

2.2. Transition Pathways electrical futures for a low carbon UK

The Transition Pathways research consortium, consisting of representatives from nine UK Universities in collaboration with E.ON and the EPSRC (Engineering and Physical Sciences Research Council), have proposed three different scenarios for how the UK energy landscape will develop up to 2050 and the resultant technology mix for the UK National Grid [13]. The three scenarios can be summarized thus:

- **Central Control:** The government is the main actor. The electricity supply mix is characterized by large, centralized schemes, predominately nuclear but also including CCS, wind farms and tidal barrages.
- **Market Rules:** Industry is the main actor. The electricity supply mix is characterized by large, centralized schemes predominately CCS but also including nuclear, wind farms and tidal barrages.
- **Thousand Flowers:** Consumers/citizens are the main actors. The electricity supply mix is characterized by smaller, decentralized schemes, including gas and biomass district heating and solar. Energy efficiency and demand reduction have the greatest significance in this scenario.

The total electricity supply from CHP schemes in 2050 is 52 TWh(e) for the Market Rules and Central Coordination scenarios and 88 TWh(e) in the Thousand Flowers scenario. The scenarios do not expressly split the supply capacity by sector. However a considerable amount of the CHP capacity in the Thousand Flowers scenario is in the form of district heating systems and domestic micro-CHP, hence it can be assumed that industrial CHP capacity for all scenarios is within the limits set by DEFRA [12]. In all scenarios the highest proportion of supply is from renewable fuelled CHP schemes, 25 TWh(e) in the Market Rules and Central Coordination scenarios and 61 TWh(e) in Thousand Flowers. In all scenarios 21 TWh(e) of electricity is supplied by natural gas fired CHP schemes [14].

2.3. Overview of the case study CHP plant

The case study CHP plant was constructed and commissioned and handed over to its current operators in 2000, under a 20 year contract agreement. The plant is under contract to supply a local soda ash works with 280 MW(th) in the form of intermediate and low pressure steam, which equates to 2450 GWh of heat a year. Power generation is limited to around 104 MW(e), giving an annual power generation of 911 GWh (around 75 MW(e) is supplied to the National Grid after the power demands of the soda ash works and the CHP site itself have been met). Gas consumption is reported to be around 3940 GWh per year. The water consumption for steam production is around 8.5 Mt per year and is approximately 50% 'raw' water, which is drawn from two local reservoirs, 36% waste hot water from the soda ash works, a maximum of 1% potable water and 12% condensate return from the steam supplied. An additional average of 8.3 kt a year of 'raw' water is used for quench water on site [15].

The heat demand is dominant and the penalties for heat interruption are severe. Hence delivering heat that is 'wasted' by, or a by-product of, power generation is not a feasible option. The power generation was introduced to improve the economic viability of the plant. The generators run at less than full capacity as the power is limited to match the heat demand.

The plant consists of: two GE 6B 40 MW gas turbines, two heat recovery boilers, one 60 MW back pressure steam turbine, a water treatment plant, a polisher or de-aerator unit for satisfactory condensate return and three back-up auxiliary boilers. Fig. 1 shows a process diagram of these components. Site assets also include the steam and power mains that connect the CHP Plant with the soda ash works site and the National Grid.

3. Method: life cycle assessment

Life Cycle Assessment, or LCA, is a way to account for the environmental burden of a given product or service across its whole lifetime, from material extraction to manufacture to use to disposal

or from 'Cradle to Grave'. The ISO (International Standards Organisation) standards ISO 14040:2006 [16] and ISO 14044:2006 [17] state that an LCA must include the four phases of:

1. Goal and scope: outlining the system boundary and level of detail and the intended use of the study.
2. Inventory analysis: here the data necessary to meet the goals of the defined study is collected into a life cycle inventory, LCI.
3. Impact assessment: the purpose of the life cycle impact assessment, LCIA, is to provide additional information to help assess a product system's LCI results so as to better understand their environmental significance. At this phase, all relevant inflows and outflows identified at the Inventory phase will be at least 'classified' into a given set of impact categories and then 'characterized' so that each impact category can be represented as a single appropriate inflow or outflow.
4. Results interpretation: the results of an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition

4. Goal and scope

A site specific life cycle inventory, LCI, was developed for an existing UK CHP plant using data collected on site visits and via discussion with plant engineers. Remaining data gaps are filled using the EcoInvent [18] database. The premise of this study is that CHP technology allows for the exploitation of industrial heat production for electricity generation, hence the focus is on the impact associated of the electricity generation.

The software package SimaPro 7.3 [19] is used to compile the inventory and subsequently apply the life cycle impact methodologies of Cumulative Energy Demand v1.07 [20] and IPCC 2007 GWP 100a [21].

The Cumulative Energy Demand v1.07 [20], or CED, method is based on EcoInvent [18] data and was developed by PRé Consultants. It is a 'single issue' assessment methodology as it focuses on

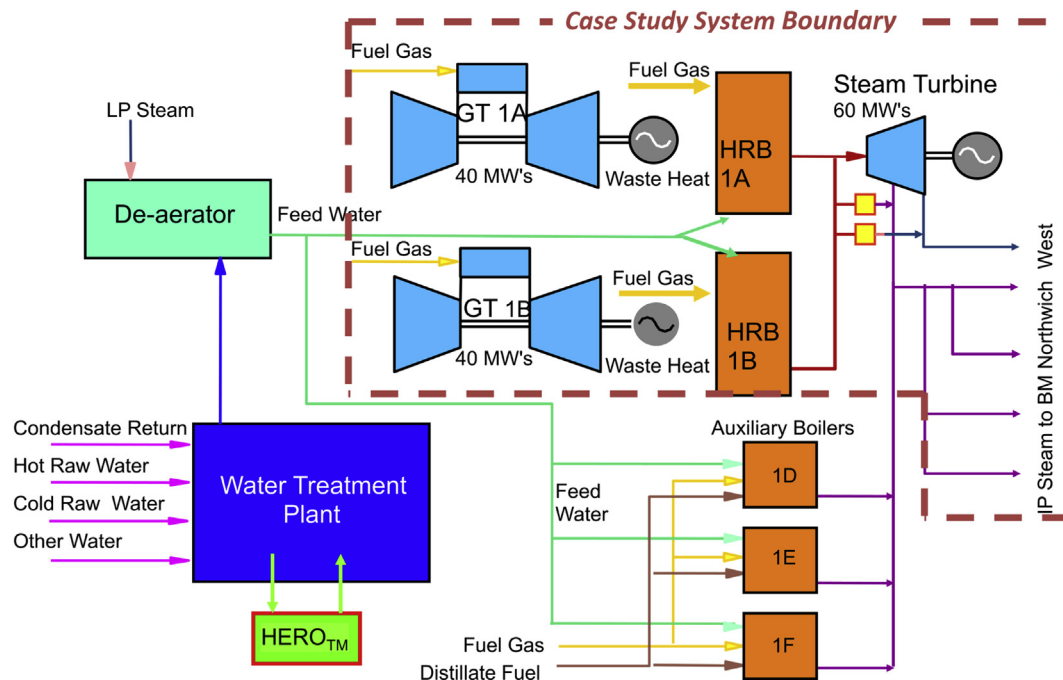


Fig. 1. Process diagram of the case study CHP system [13].

the life cycle energy demand alone. CED classifies each energy demand into the 5 categories of: 1. Non-renewable, fossil; 2. Non-renewable, nuclear; 3. Non-renewable, biomass; 4. Renewable, wind, solar and geothermal and; 5. Renewable, water. The characterized unit for all categories is MJ equivalent, although characterization in its full sense is not really required as all relevant inflows are, by definition energy.

The IPCC 2007 [21] succeeds the IPCC 2001 method developed by the Intergovernmental Panel on Climate Change. The 100a version is used, which contains the climate change factors with a timeframe of 100 years. All air emissions with a global warming potential or GWP, according to the IPCC, are classified into a single category and then characterized with reference to CO₂, hence the characterised unit is kg.CO₂ equivalent. Study boundaries.

The plant is assumed to have lifespan of 30 years. The CHP inventory is compared to the Ecoinvent database entry for 'steam, for chemical processes' [22] in order to investigate CHP in comparison to heat only generation. Therefore the study boundary is set to exclude anything that is not reasonably comparable. As a result, the back-up boilers, the de-aerator unit and the auxiliary energy or resource demands associated with plant staff and buildings are excluded from the inventory. The system boundary is depicted in Fig. 1 and shows the plant hardware that is included in the inventory. The electricity demand of the site itself is met by the plant, however whether the power generated is consumed on or off site is irrelevant to the assessment.

4.1. Summary of main assumptions

- A CHP unit has a design life of 30 years.
- The implementation of CHP technology does not displace any current heat production infrastructure i.e. the disposal of current system is not allocated to the installation of the CHP system.
- The life cycle impact of the CHP unit generators can be assessed using the only the life cycle inventory presented.
- The impact of equivalent heat and electricity produced by separate, conventional, energy generators can be determined using data from the Ecoinvent database, edited only to ensure that the fuel supply representation is the same as that used in the CHP inventory.
- The CHP technology in the case study and in the UK wide extrapolation is implemented to exploit an existing industrial heat production for electricity generation i.e. is heat lead.
- The allocation of impact between heat and electricity production is explored using two methods. The preferred being termed 'fixed heat' allocation, where the impact of the heat production is assumed to be equal to that of heat produced by a heat only system and only the impact that is over and above that is allocated to the heat production. A second method adopted from the DUKES (Digest of United Kingdom Energy Statics) publications is based on the assumption that electricity production is half as efficient as heat, so impact is allocated using a simple 1:2. The DUKES method yields a more conservative result for electricity production so is included in all comparisons for reference.

5. Life cycle inventory analysis

5.1. Construction/hardware

- *On site Construction Works:* No site specific data was available for the installation and commissioning activities. Hence the Ecoinvent dataset for the construction works for a 160 kW(e) cogeneration unit [23] has been used scaled according to site area.
- *National Grid Connection:* No site specific data for the additional infrastructure required for connection to the National Grid was

available so an adaptation of data from Ecoinvent was used. Inventory data for the grid connection for 30 kW, 150 kW, 600 kW and 800 kW onshore wind farms [24] was used to make a scaled estimate for the required connection infrastructure and its disposal.

- *Gas Turbine:* According to data provided by E.On staff [25], the GE 6B model has a 'packaged power plant' mass of 315 t, inclusive of the mechanical drive system, i.e. the turbine itself plus gearbox and fuel and lubrication systems, which has a reported mass of 86.4 t. Documentation obtained from site states that the gas turbine gearbox has a mass of 12 t [26], hence it has been assumed that the gas turbine itself, inclusive of fuel and lubrication systems, has a mass of 74.4 t. The Ecoinvent inventory entry for a 10 MW gas turbine assumes that nearly all the mass of the turbine is steel, with approximately 95% reinforcing steel and the remaining 5% chromium, or stainless, steel. This proportional split is adopted for the case study gas turbine yielding a material inventory of 4.5 t of average processed chromium steel and 69.9 t of average processed reinforcing steel. The gearbox and remaining mass of the package plant, which is assumed to consist of the compressor, combustor, auxiliary starting system and other connecting parts, is simply represented as 132 t of average processed reinforcing steel.
- *Steam Turbine:* Documentation obtained from site states that the steam turbine has a total mass of 90 t [27] and that it drives a synchronous generator via a rigid coupling, hence there is no gearbox. Data obtained from E.On staff regarding the steam turbine shows that the larger turbine sub-components, e.g. the casing and rotor, would be steel and a few of the smaller sub-components, the largest of which being the blades, would be stainless steel i.e. with a chromium content of more than 11% [28], which supports the proportional split adopted for the gas turbine. Discussions with E.On staff and specialists at the University of Bath have indicated that the mass difference between the gas and steam turbines, that is 74.4 t versus 90 t, would be largely due to the thicker casing walls required for a steam turbine, hence it is assumed that the additional mass of the steam turbine is entirely cast steel, yielding a material inventory of 4.5 t of average processed chromium steel and 85.5 t of average processed reinforcing steel. Steam turbines are a simpler technology than gas turbines, so it is assumed that this is sufficient to represent the full steam turbine 'package'.
- *Generators:* The steam turbine generator has a mass of 130 t [27], and the gas turbine generators, exclusive of gearbox, have a mass of 108.45 t [26] each. A detailed bill of materials was made available by E.On staff for the generator for the 800 MW steam turbine at the proposed Kingsnorth power station, consisting mainly of reinforcing steel, copper wire and rock wool insulation, each subjected to material appropriate average manufacturing processes, with a total mass of 575 t [29]. This data was scaled by mass in order to represent the three generators required for the case study CHP inventory.
- *Heat Recovery Boilers, HRB:* Boilers of some sort would of course be required in any industrial steam production process. The only notable difference is that the HRB in a CHP system would be rated to produce steam suitable for the steam turbine rather than the for the customer use (the steam turbine, however, is rated so that the exhaust steam is suitable for the chemical works). One HRB in the case study CHP has a mass of 480 t and is predominately steel [30]. Hence a simple representation of 480 t of average processed reinforcing steel is used for each HRB. The Ecoinvent database entry for 'steam, for chemical processes' [22] accounts for hardware via the use of 'gas burned in industrial furnace' in its inventory rather than 'gas at consumer' [31].

- **Turbine and HRB Shipping:** Correspondence with the sales team at GE suggests that the steam and gas turbine components would have been manufactured in Belfort in eastern France [32]. It has been assumed that this is also the case for the HRBs. Components are assumed to travel by lorry from the factory to Brest, then by container barge to Liverpool, and then by lorry again to site. This shipping schedule is represented in the inventory using transport entries in the Ecolnvent database [18] and distance calculations from Google Maps [33].
- **Steam Mains:** Two 4.8 km API 5 L Grad B Carbon steel pipes, insulated with a 150 mm thickness of rock wool connect the CHP plant with the soda ash works in order to deliver the steam.
- **Water Treatment Plant, WTP:** Specific data for the chemical and water requirement of the WTP were made readily available, however no detailed inventory data on the hardware requirements has been identified. Hence for the case study inventory it is assumed that all water is 'tap water' for which the Ecolnvent database entry [34] inherently accounts for all hardware, process and chemical requirements. This is also in line with the inventory of the Ecolnvent database entry for 'steam, for chemical processes' [22].

Table 1 presents a summary of the inventory data for the construction stage of the case study CHP.

5.2. Operation and maintenance

- **Fuel:** the fuel type is represented by, 'natural gas, high pressure, at consumer/GB' taken from the Ecolnvent database [31].
- **Lubrication Oil:** No measured data was available for the actual oil consumption for the case study plant. Published studies of gas fired cogeneration plants provide values of 0.5 mg/MJ_{in} [35], 0.1 g/kWh(e) [36] or 0.4 g/kWh(e) [23]. In accordance with the cautionary principle the, latter estimate was adopted as it yields the greatest total consumption of 11 Mt over the plants 30 year lifetime.
- **Emissions and Waste:** Annual emission and waste production data was taken from the 'Pollution Inventory Reports' submitted by the plant to the Environment Agency. There is limited information available as to the nature of the toxic waste but this is probably used oil and the sludge produced by the water treatment plant, so it is possible that its inclusion could lead to some double counting as the water is assumed to be 'tap water'. However, as a breakdown

Table 1

Table of life cycle inventory data for the construction stage of the case study CHP.

Component/Ecolnvent dataset	Material	Quantity (t)	Scaling factor	Supplier location	Journey	Transport type	Distance (km)
On site works							
'Construction work, cogen unit 160 kWe/RER/IU' [21]		n/a	280	n/a	n/a	n/a	n/a
National grid connection							
Edit of 'Wind power plant 800 kW, moving parts/RER/I U' [22]	Aluminium	0.00004	12.3	n/a	n/a	n/a	n/a
	Copper wire	15					
	Polyethylene	7.3					
	PVC	5.3					
	Steel bar, low-alloyed	0.063					
	Lead	0.0005					
	Tin	0.0005					
	Polypropylene	0.02	1				
GE 6B gas turbine ×2				Belfort, France			
Turbine plus fuel & lube systems	Machined steel	69.9	n/a		Belfort, France – Brest, France	Road	1047
	Machined stainless steel	4.5					
Compressor	Machined steel	120	n/a				
Combustor							
Bearings							
Auxiliary starting system							
Hydraulic supply system							
Electronic control system							
Dry low NoX system							
Gearbox	Machined steel	12			Brest, France – Liverpool, UK	Ship	723.35
Alstom back pressure steam turbine							
Turbine plus fuel & lube systems	Machined steel	85.5	n/a				
	Machined stainless steel	4.5					
Gas turbine generator ×2							
Stator: from Kingsnorth Inventory, for 800 MW ST	Rolled steel sheet	300	0.189		Liverpool, UK – Winnington, UK	Road	47.83
	Steel plate	65					
	Copper wire	75					
	Rock wool insulation	5					
Coolers: from Kingsnorth Inventory, for 800 MW ST	Copper finned tubes	24					
	Steel tubes	10					
Rotor: from Kingsnorth Inventory, for 800 MW ST	Machined steel	70					
	Copper drawn bars	24					
	Glass fibre insulation	2					
Steam turbine generator from Kingsnorth Inventory, for 800 MW ST	As above	As above	0.226				
Heat recovery boilers ×2							
Heat recovery boiler	Machined steel	480	n/a				
Steam mains							
Pipework	API 5 L, carbon steel, 50 cm OD	9.6 km	n/a	n/a	n/a	n/a	n/a
Insulation	Rock wool insulation, DN 400, 30 mm	302 km					

of the exact nature of the waste was not available, an average toxic waste mix was included for the full reported amount. Similarly, as no detailed information of the sources of the municipal waste was available, an average mix of the full reported amount is included.

- **Deliveries to Site:** An estimate for the annual transportation of goods to site was calculated using a list of postcodes of the origin of all deliveries to site for the year 2011 from the site records. For each postcode the driving distance to site was estimated using Google Maps [33] and that distance was assumed to be traversed by a 16–32 t truck or a transoceanic freight ship where appropriate. Any delivery vehicle arriving on site would also have to make a return journey but also vehicles would typically make multiple deliveries in a trip. This level of detail is not available so only allocating the outward journey was deemed to be satisfactory compromise.
- **Turbine Maintenance:** The turbines at the studied plant have a major maintenance event planned every 10 years of life. One major maintenance event is estimated to equal approximately 80% of the work and hardware requirements of the original construction [37]. Hence, each turbine, steam and both gas, is assumed to have maintenance demand equivalent to 160% of construction during the plants 30 year lifetime.

Table 2 presents a summary of the inventory data for the operation stage of the case study CHP.

5.3. Decommission and disposal

No site specific data was available for the decommissioning of the case study CHP plant. However, because of the high value of the metals that make up the nearly all of the plant hardware, it is very likely that these parts will be reused or recycled. Recycling is typically of a higher environmental impact than reuse so, in accordance with the precautionary principle, it has been assumed that all steel and copper parts are recycled at the end of life. The small amounts of other materials are assumed to be sent to landfill. The disposal scenario included in the scaled inventory entry for national grid connection assumes that the non-metal parts are incinerated [24].

6. Results interpretation

Firstly, the representativeness of the case study inventory was investigated via comparison with the Ecolnvent database entry for

a mini CHP system [38], fuelled by Great Britain specific gas supply [31]. Figs. 2 and 3 compare the energy demand and GWP of the two inventories respectively. The Ecolnvent representation is around 3% less energy intensive than the case study CHP but this minimal and is explained by an almost identical percentage difference in the gas consumption. The difference between the GWP results is due almost entirely due to operational emissions, the case study inventory uses site specific data and the Ecolnvent representation is averaged data for total Swiss CHP emissions. A difference of this magnitude is well within expected limits. Such a close result lends confidence that both inventories are acceptable representation from which to make estimates.

These total impact estimates for the case study CHP scheme can now be used to calculate the energy and carbon savings compared to separate heat and power generation. The case study CHP generates 911 GWh(e) of power and 2450 GWh(th) of heat annually. Table 3 provides the information required to calculate the energy and carbon savings for the studied CHP scheme as estimated using database entries available from Ecolnvent [18], adapted for a GB specific gas supply. The case study CHP delivers a total energy saving of around 16% and a GWP saving of 21% in comparison to separate energy generators.

6.1. System energy analysis

The energy gain ratio, EGR, is given by:

$$\text{Energy generated/Energy demand} \quad (1)$$

As already stated the annual power generation of the studied CHP plant is 911 GWh(e) and the annual heat generation is 2450 GWh(th), which is equivalent to 3.2 PJ and 8.8 PJ respectively. Hence the EGR of the case study CHP is 0.8. This value is less than 1 demonstrating that the system demands more energy than it generates, which is to be expected as the energy demand is inclusive of fuel. A fossil fuelled power generation system cannot deliver more energy than it consumes as this would defy the first law of thermodynamics. For comparison, a gas fired power only system and a gas fired steam only system have estimated EGRs of 0.5 and 0.8 respectively.

The energy payback is the time it will take for the energy generated to exceed the energy consumed over the plant's lifetime. The energy payback period in years is given by:

$$\text{Total lifetime energy demand / Annual energy generation} \quad (2)$$

Using the total annual energy generation value of 12 PJ and the total energy demand estimate of 429.6 PJ, a system payback period of 36 years can be calculated, which is longer than the plant's lifespan. This is also to be expected, as it is also thermodynamically impossible for a fossil fuelled power generator to payback within its

Table 2
Table of life cycle inventory data for the operation stage of the case study CHP.

	Unit	Annual amount	Lifetime amount (30 years)
Operational flows in: resource			
Fuel (natural gas (Jungbluth, 2003))	GWh	3942.0	118 260.0
Lube oil	t	364.4	10 932.5
Water ex. condensate return (tap water (Jungbluth, N, 2005))	kt	4347.5	130 425.0
Deliveries	km (Road)	17 325.9	519 777.8
	km (ship)	4156.4	124 690.9
Operational flow out: emissions & waste			
Carbon dioxide	kt	751.0	22 530.0
Carbon monoxide	t	159.5	4785.0
Methane	t	53.5	1605.0
Nitrogen oxides	t	351.5	10 545.0
NM VOC, non-methane volatile organic compounds	t	13.0	390.0
Particulates, <2.5 µm	t	8.6	258.0
Particulates, >10 µm	t	11.6	348.0
Sulphur dioxide	t	41.8	1254.0
Toxic waste	t	51.6	1548.0
Municipal waste	t	145.4	4362.0

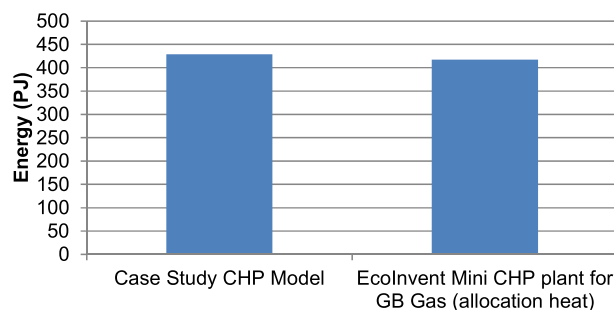


Fig. 2. Inventory comparison by energy demand.

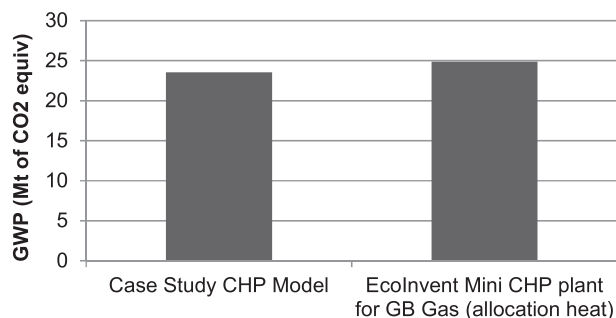


Fig. 3. Inventory comparison by GWP.

lifetime if fuel demand is included in the total energy demand estimate. For comparison, a gas fired power only system and a gas fired steam only system each with a lifetime of 30 years have estimated energy payback periods of 59 years and 36 years respectively.

The estimates suggest that the case study CHP provides little improvement over steam only production. The energy benefits are found with respect to the power generation only. This synergizes with the study assumption that the CHP technology is installed only in order to exploit the heat demand for the generation of low impact electricity.

6.2. Energy and emission allocation comparisons

In order to assess the impact of the electricity generated by the CHP plant, the overall lifetime impact must be allocated between the heat and power generated. The allocation method used in the Digest of UK Energy Statics, DUKES, to allocate emission intensity between heat and power is based on the adopted method of fuel demand which assumes that electricity generation is half as efficient as heat generation and therefore fuel demand, and emissions, can be allocated using a simple ratio of 1:2 [8]. This allocation method would lead to discounting the emissions associated with heat also. This type of allocation can only really be justified in instances where there is a direct demand for both the heat and power. When converting to a CHP from a heat only technology, as would be the case in many industrial systems, arguably the emissions allocated to the heat production should remain fixed and only the emissions that are above the previous heat only system are attributable to the power generation. In both allocation methods the overall saving will be the same, but the different associated savings with the power generation is important in order to evaluate the contribution CHP conversion can make to UK low carbon electricity supply. Fig. 4 compares the resultant allocations when the two methods are applied to the estimated total energy demand of the case study CHP and Fig. 5 makes the same comparison for the estimated GWP. As would be expected the 'fixed heat' method gives

Table 3
Information required to calculate impact savings.

	Energy demand, PJ	GWP, Mt.CO ₂ equiv
Impact of 911 GWh of gas fired electricity production [37]	6.3	0.37
Impact of 2450 GWh of gas fired steam production for chemical processes [20]	10.7	0.62
Case study CHP, total impact	429.6	23.54
Case study CHP, annual impact (total system impact/30 years)	14.3	0.78
Case study CHP, annual impact savings	2.7	0.21

Emboldened data shows the saving.

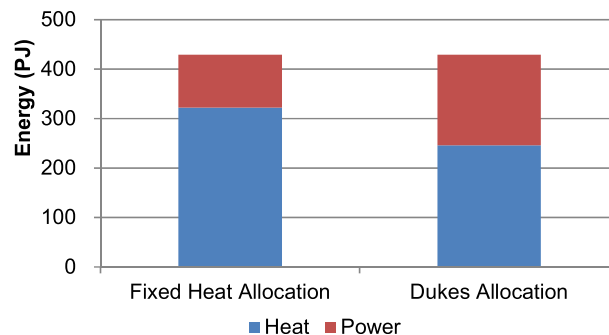


Fig. 4. Comparison of energy demand allocation.

a much lower impact allocation to the electricity generated in both cases, around 59% less energy demand and 42% less GWP; although, this is obviously offset by an equal impact reduction for heat using the DUKES method. Given that the premise of this study limits it to CHP plants that exploit an existing industrial heat production for electricity generation, the 'fixed heat' method is preferred. However, the DUKES method is included so that the results may be more easily transferred to other situations and as a maximum, reasonable estimate.

These two options for the impact values for industrial CHP power generation can now be used to investigate the impact savings available in comparison to power production by the National Grid. Fig. 6 compares the two estimated values for energy demand per MWh generated with five representations of the National Grid: as it was in the baseline year 1990, as it is in the (approximate) present, and to the three Transition Pathway future grid mixes for 2050 [39]. The very small negative score for the case study CHP using the fixed steam allocation is because the overall results for the plant had a lower demand for nuclear and renewable energy than the EcoInvent database entry for 'steam, for chemical processes' [22]. All the National Grid representations have a higher total energy demand than either of the representations for power from the case study CHP plant, including the three Transition Pathway estimates for the 2050 grid mix. However, a high proportion of the energy demand of the future grid scenarios is made up from nuclear and renewable sources. If the energy demand from non-renewable fossil fuels is isolated from the total values, the results for the case study CHP start to look less favourable. The fossil fuel demand of the case study CHP electricity supply exceeds that of all the future scenarios if the DUKES allocation method is applied. If the 'fixed steam' allocation method is applied then the fossil fuel demand still exceeds the Central Coordination and Thousand Flowers scenarios, by about 12% and 4% respectively. However, there is a benefit compared the Market Rules scenario. This is because of the high

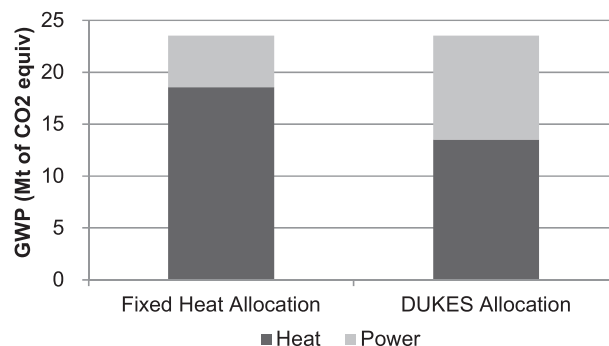


Fig. 5. Comparison of GWP allocation.

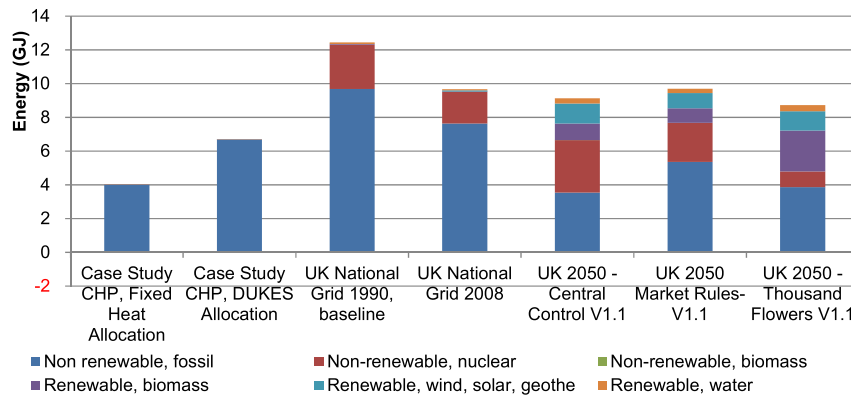


Fig. 6. Comparison of specific energy demand (per 1 MWh(e) generated).

proportion of gas and coal fired generation using carbon capture and storage, CCS, technology in this scenario.

Fig. 7 compares the two estimated values for GWP per MWh generated with the same five representations of the National Grid. The GWP for both value estimates for CHP electricity falls below estimates for both the current and 1990 baseline National Grids. Carbon equivalent savings per MWh of generation are estimated at 377 kg or 193 kg against the 2008 grid and 629 kg or 445 kg against the 1990 baseline, depending on the allocation method applied.

Importantly, when the 'fixed heat' allocation is applied, the saving against the 1990 grid represents 77%, which almost meets the UK carbon reduction target. However, both values for the GWP of CHP electricity exceed all future scenario estimates. The proportional difference is greater than that of the fossil fuel demand because of the CCS technologies present in all the future scenarios which keep carbon intensity down despite fossil fuel combustion. Carbon equivalent gains per MWh, reach 95 kg or 280 kg against the Central Control scenario, 71 kg or 255 kg against the Market Rules scenario and 86 kg or 271 kg against the Thousand Flowers scenario. This result supports the suggestion that primary fuelled CHP may eventually cease to offer any carbon benefit over an increasingly decarbonized National Grid and will become a carbon burden.

7. Implications for UK-wide application

In 2010 reported industrial CHP electricity generation totalled 24 TWh(e). Estimates for UK wide industrial CHP potential are based on the year 2010 as that is the most recent year for which most data is available at time of writing.

Via comparison with the case study CHP, a simple prediction can be made for the additional generation potential available from

industrial heat for CHP across the UK. In the case of the studied CHP scheme a heat load of 2450 GWh(th) leads to a generation of 911 GWh(e). Applying this ratio, the UK wide remaining annual industrial heat load of 110 TWh(th) could lead to an electricity generation power of 41 TWh(e). Hence a maximum theoretical potential electricity generation can be estimated:

$$24 \text{ TWh(e)} + 41 \text{ TWh(e)} = 65 \text{ TWh(e)} \quad (3)$$

Using the results of the study, it can also be estimated that this generation capacity would give rise to a total GWP of 11.4 Mt.CO₂ equivalent or 23.5 Mt.CO₂ equivalent, using the 'fixed steam' or DUKES allocation methods respectively.

In 2009, the UK electricity supply reached a total of 384 TWh [40] and reported emission figure for that year is 157 Mt.CO₂ (equivalent) [42]. Hence, the remaining industrial heat load resource could have provided 11% of the power supply at 5% or 10% of the emissions in 2010, dependant on allocation method and assuming natural gas fired systems.

7.1. What is the potential contribution to the UK carbon reduction target?

The results presented have demonstrated that gas fired industrial CHP has the potential to generate electricity at just over a 77% carbon saving compared to the 1990 baseline National Grid which almost meets the carbon reduction target of 80%. Although this drops to 55% when the DUKES allocation is applied, it must be remembered that this will be offset considerably by a reduced carbon allocation to the heat generation, however the 1990 heat data is not available to calculate the exact saving. However, coming close to or even meeting the target may not be as good as it seems. It is likely that the electricity supply sector will have to achieve

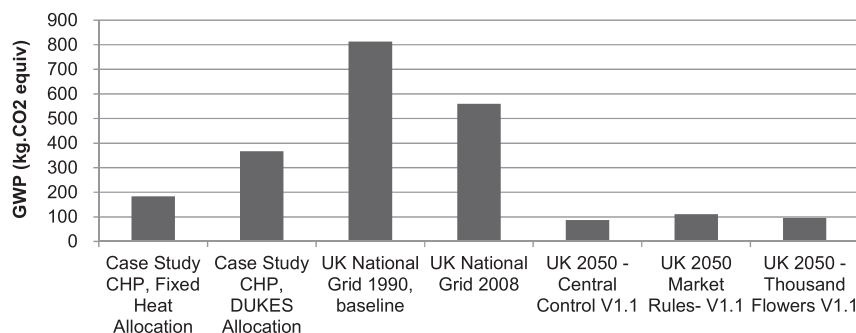


Fig. 7. Comparison of specific GWP (per 1 MWh(e) generated).

considerably better than the 80% reduction target to compensate for the heat and transport sectors were reductions are predicted to be much harder to achieve.

7.2. Fossil fuel demand

The study also demonstrates that converting from a heat only system to a CHP system will lead to an additional 4 GJ of energy demand from primary fuel per MWh generated. This implies that if an additional 41 TWh(e) were to be generated via CHP conversion, an additional 164 PJ of primary fuel would be consumed in the UK.

7.3. Contribution to the Transition Pathways future scenarios

If it is assumed that the power supplied by natural gas fired CHP in each of the Transition Pathways scenarios is derived from industrial conversions, then the results of the study can also be used to assess the technology contribution. Each scenario has an equal contribution from gas fired CHP of 21 TWh(e). This implies an emission total of 3.7 Mt.CO₂ equivalent or 7.7 Mt.CO₂ equivalent, depending on which allocation method is applied. The study has shown that electricity generated by industrial CHP has a greater carbon impact than that of all the Transition Pathway technology mixes per MWh generated. However, it is arguably unfair to compare a single technology to an overall value for the National Grid, as the grid mix will, by definition, be made up of a number of technologies with a range of carbon intensities. The fact that CHP electricity appears unfavourable by comparison does not necessarily imply that it cannot contribute. However to investigate this, a 'whole system appraisal' of the technology mixes is required and it is the intention of this study to inform that appraisal rather than conduct it.

8. Conclusion

The UK industrial sector contributed 33% of the national greenhouse gas emissions in 2010 [2]. This is due to the high proportion of carbon intense fuels used to generate heat. Combined heat and power, CHP, technologies use the primary fuel more efficiently by simultaneously generating electricity and useful heat. Industrial process heat supply is ideal for the application of CHP, as the technology is most efficient where there is a constant and 'real' heat demand. An energy and carbon life cycle assessment was completed on an existing natural gas fired CHP plant which has an annual output of 911 GWh(e) of power and 2450 GWh(th) of heat. The plant was found to have a total lifetime energy demand of 429.6 PJ and a lifetime GWP of 23.54 Mt.CO₂ equivalent. Assuming a 30 year lifetime, this gives average annual energy demand and GWP of 14.3 PJ and 0.78 Mt.CO₂ equivalent, respectively. Using the energy output data provided and the estimated energy demand, an energy gain ratio of 0.8 and an energy payback period of 36 years was calculated for the plant. Conversion from a heat only system to a CHP system will lead to an increase in energy demand and GWP. However, the study has shown that the additional impact cost leads to considerable impact savings when the total energy generation is compared to the sum impact of separate heat and power generation. Annual energy demand savings of 2.7 PJ and GWP savings of 0.21 Mt.CO₂ equivalent were identified. It was also shown that considerable impact savings are available when the electricity only is compared to the current and 1990 baseline National Grids. Importantly the study has demonstrated that industrial CHP has the potential to generate electricity at a 77% carbon saving per MWh compared to the 1990 baseline National Grid. Exploiting the available industrial heat load to generate electricity via CHP clearly

has significant potential to reduce carbon emissions and to improve energy efficiency in the immediate term. However, when the power supply is compared to potential future grids, the benefits become less obvious. The study has shown that GWP potential of primary fuelled CHP is likely to exceed that of the 2050 National Grid per MWh generated. It is also likely that the fossil fuel demand will exceed that of the 2050 National Grid, however this is dependent on the proportion of CCS technology deployed. This suggests that other low carbon and/or renewable electricity generators should be prioritized for incorporation into the grid mix and that alternative and/or additional methods for decarbonizing industrial heat should be investigated.

Acknowledgement

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